Compact Low Temperature Actuators for Lunar Robotic Systems

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Technical Challenge
Low Temperature Mechanism

What are we trying to do?

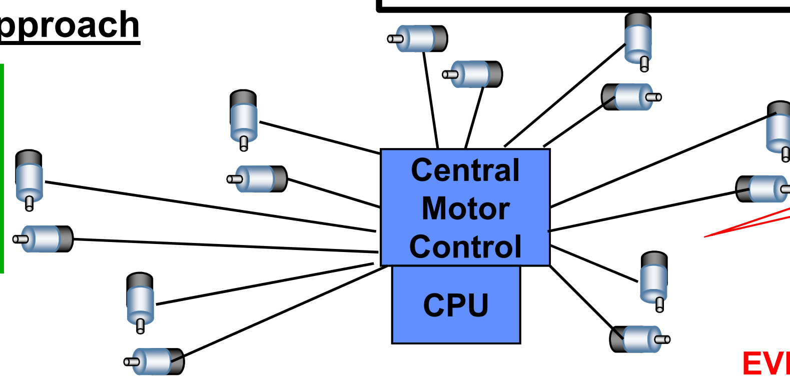
Revolutionizing the design of next generation space systems with low temperature motors, drive electronics, gearboxes, actuators, Seals and dry lubricants all integrated together for extreme environment of space

Why?

- Eliminate power and hardware for active heating
- Reduced actuator mass,
- Enhanced actuator performance over wide temperature
- Reduced number of wiring
- Enhanced modularity and scalability
- Simplified ATLO procedures

Traditional Centralized Approach

1000 – 2000 wires out of the chassis

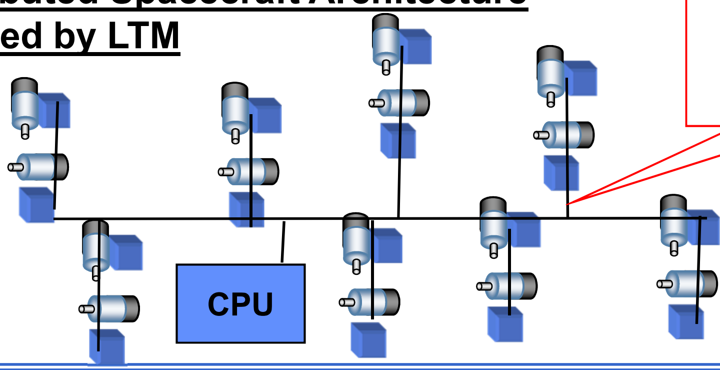


Many wires to each motor

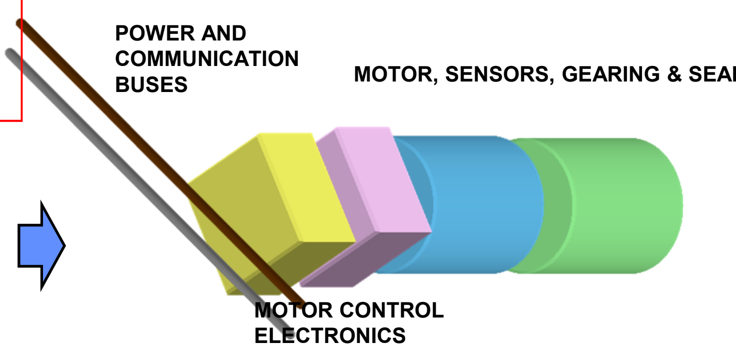
WIRES EVERYWHERE

MER REM THERMAL TEST

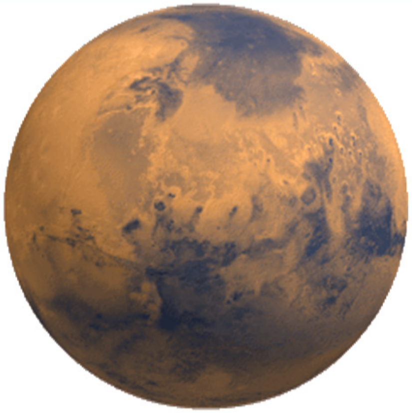
Distributed Spacecraft Architecture enabled by LTM



Standard bus shared by all motor



State of Practice: Actuators for Mars



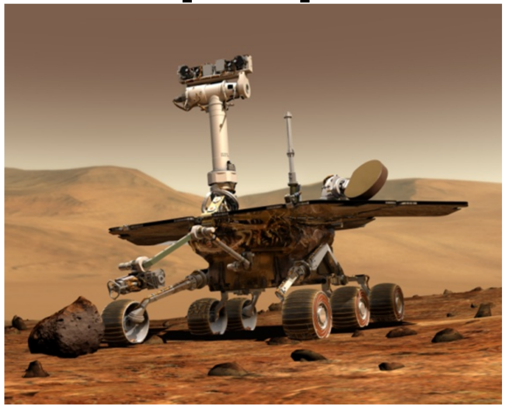
Temperature Range

[-125°C , 20°C]

Mars Path Finder [1997]

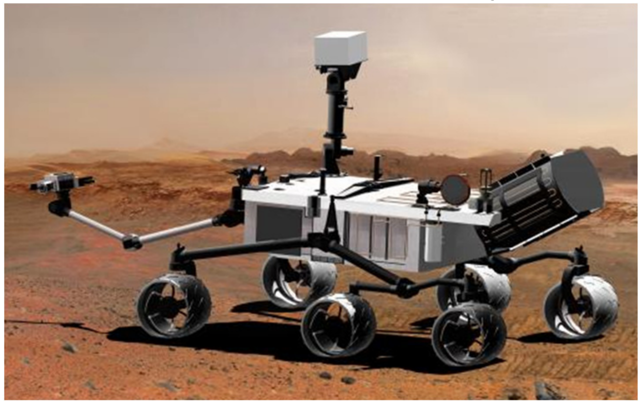
6-10 actuators

Mars Exploration Rover [2003]



20-25 actuators

Mars Science Laboratory [2011]



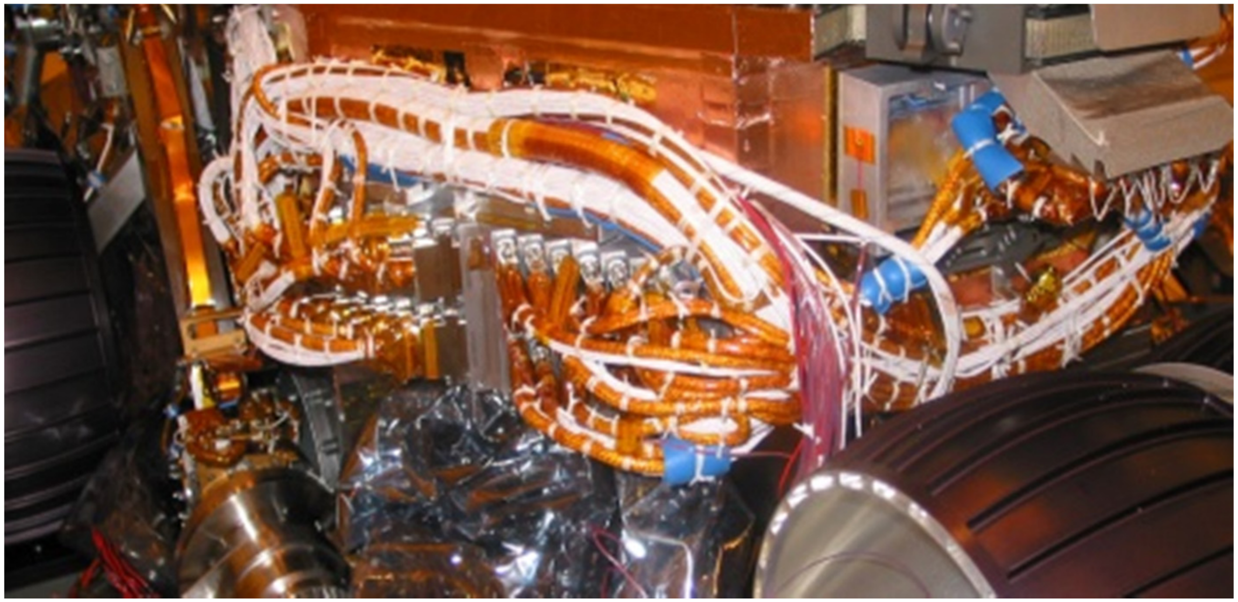
40 actuators

Phoenix Lander [2007]

10-12 actuators

- Centralized WEB based architecture
- Wet lubricated and heated actuators

State of Practice: Actuator Control Wiring



MER Actuator wiring Harness

- Physical Constraints
  - Higher Weight
  - Higher Volume

Higher Mission Cost

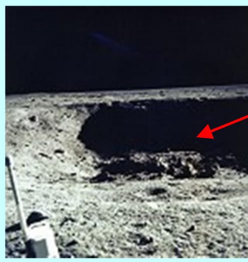
- Electrical Limitation
  - Electro Magnetic Interference (EMI)
  - Electrical Power
  - Noise

State of Practice: Lunar Systems

Hardware tested in Moses Lake

Lunar Surface Temperature:
120C Days, -180C Nights

Excursions into permanently shadowed craters (as low as -233 ^{o}C)



Shading by local topography

Hardware located on appendages

Self shadowing of hardware

Operations during night cycle

Payload Handling: Lunar Crane

Rover: Lunar CHARIOTT

Cargo Carriers: ATHLETE

- Wet lubricated and heated actuators
- Electronics in “Warm Electronic Box” (WEB)

Technical Challenge: Low Temperature Mechanism (Motors, Bearing, Gears, Position Sensor, Electronics)

How is it done today, what are the limits of current practice?

- Heat loop to force-keep actuator at -55C to -70C
- Liquid lubricated long life actuators (brushless DC motors, bearing and gears) capable of operating to -55C
- Position sensors(magnetic/ optical) capable of operating to -55C
- Actuator electronics kept in WEB operate to -55C
- Seals operate to -120C

What is new in our approach?

- Wide Temp./Long Life by Design: Brushless DC motor, bearings and Gears enhance to support operating to -230C.
- Dry Lubricant Film (bearings and gears) eliminates the traditional wet lubricant freeze-out. Produce temperature invariant drag to -230C.
- Redesigned position sensor resolver with extended temperature range of -230C.
- Wide temp SiGe based mixed signal circuits enables operation of electronics to -230C

What are the payoffs if successful?

- A revolution in design of next generation scalable highly reliable space robotic systems
- 30% power savings by eliminating heaters
- 2 order of magnitude reduction in interconnect cables
- 50% reduction in mass of electronics and electronic housings
- Order of magnitude enhancement in reliability, modularity and scalability

Low Temperature Mechanism Development

Objectives:

Develop modular low temperature mechanism consisting of Gear Box, Motor, Sensor (Resolver), and Motor Control Electronics for lunar surface systems (vehicles and Cranes) capable of operating between -230C and 120C for 5 years.

1. **Demonstrate small motor and drive system feasibility at -230 deg C,**

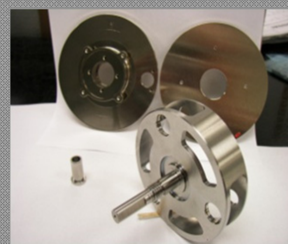
2. **Demonstrate small motor and drive system life at -230 deg C, 90M rev at -230C ambient**

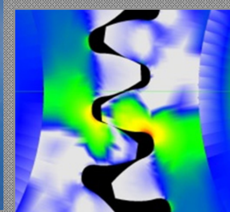
3. **Develop and life test low temperature actuator with dust seals**

Low Temperature Mechanism, Technology Definition

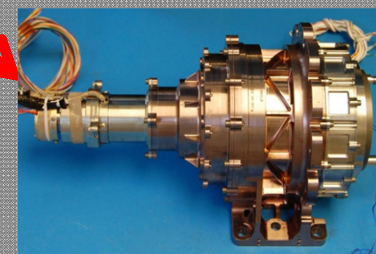
LTM revolutionizing the design of next generation space systems with low temperature motors, drive electronics, gearboxes, actuators, Seals and dry lubricants all integrated together for extreme environment of space

"State of Practice": MSL actuators motor/gearbox combination that is wet lubricated, heated and controlled from warm electronic box



Gear Box Components & Housing



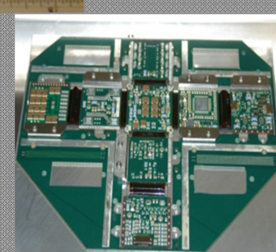
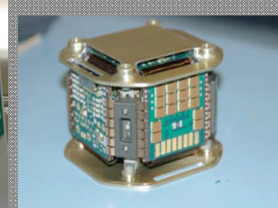
Bearings

LTM0

LTM1

Resolver

Dust seal

Control Electronics

LTM Key Performance Parameters Status

Customer Requirements/ Needs	Key Performance Parameter	State of the Art	Current Value	Threshold Value	Goal Value	Status at the end of FY 10
Lunar Rovers motor electronics operating life time of 5 years, in lunar environment	Electronics Operating life time at low temperature	10 years at -125C	10 years at - 125C	5 years at -230C	10 years at -230C	CMOS transistors and SiGe BICMOS analog circuits demonstrated to operate at -230C Motor Control COTS fail to operate at T<-170C
*10,000 Kilometer of traversing or 300 million motor revolutions	# of actuator revolution at low temperature	1E6 Rev on MER actuator with external heaters	1E6 Rev on MER actuator with external heaters	30 E6 Rev at -230C (equates to 1000 Km)	Minimum number of 450E6 rev for Mechanism at -230C	100 M rev on LTM0 demonstrated at -230C environment 1 M oscillatory rev on LTM0 at -230C
70 thermal cycles	Temperature cycles	1500 cycles at -120C to 85C	1500 cycles at -120C to 85C	100 cycles, -230C to +120C	150 cycles -230C to +120C	Not demonstrated
Output power range for mechanism for Lunar surface systems	Range of power delivered by low temperature mechanisms	100 mW to 30W at -125C	100 mW to 30W at -125C	100 mW to 2.5KW at -180C	100 mW to 2.5KW at -230C	100W to 300W demonstrated at -230C

Actuator /Electronics development metrics driven by wide temperature range, long life requirement and scalability issues.

- *Low Temperature KPPs driven by operations during lunar night, shading by local topography, self shadowing of hardware, and excursions into permanently shadowed craters.*
- *KPP for life cycles is derived from NASA HRS excursion distances.*
- *Many potential uses result in large range of required power (torque and speed). High end of scalability is ATHLETE and Chariot type users.*
- *Dust mitigation technology not introduced as KPP but will be addressed.*

Limited funding requires focused serial development. Technology is first proven for smaller actuators with emphasis on operation temperature and life determination. With adequate funding, technology can be then scaled for high end power requirements and any life issues addressed if necessary.

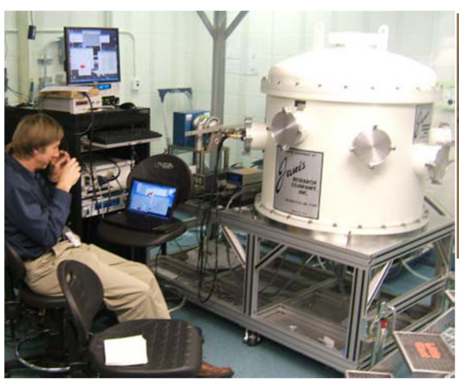
Lunar Mechanical Test Bed

Lunar Mechanical Test-Bed was setup to to evaluate and test low temperature mechanisms at LaRC.

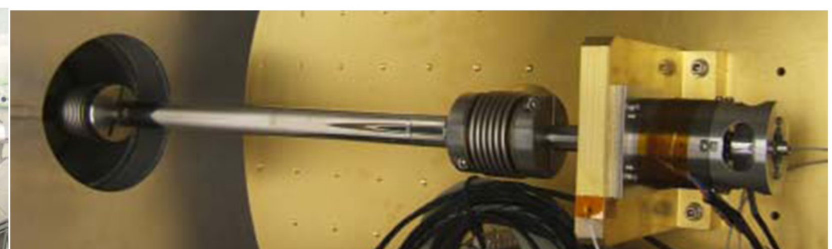
- Provides vacuum environment and temperatures as low as 14 degrees Kelvin
- Uses no consumables except power which results in a very low cost for extended testing.
- Mostly autonomous operation
- Dedicated capability to support long duration testing
- Provides the capability to torque load motors and actuators while at temperature.

Leveraged the ETDP (ETDD) Dust Project test capabilities at GRC to assess Martian seals and plans were to utilize NESC developed facilities at MSFC for testing actuators in lunar dust.

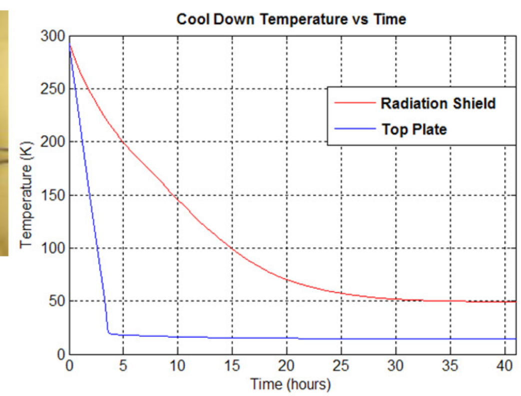
<u>Significance:</u>
Provided the capability for long term testing at very low temperatures while requiring very limited funds



LTM low temperature test bed at LaRC



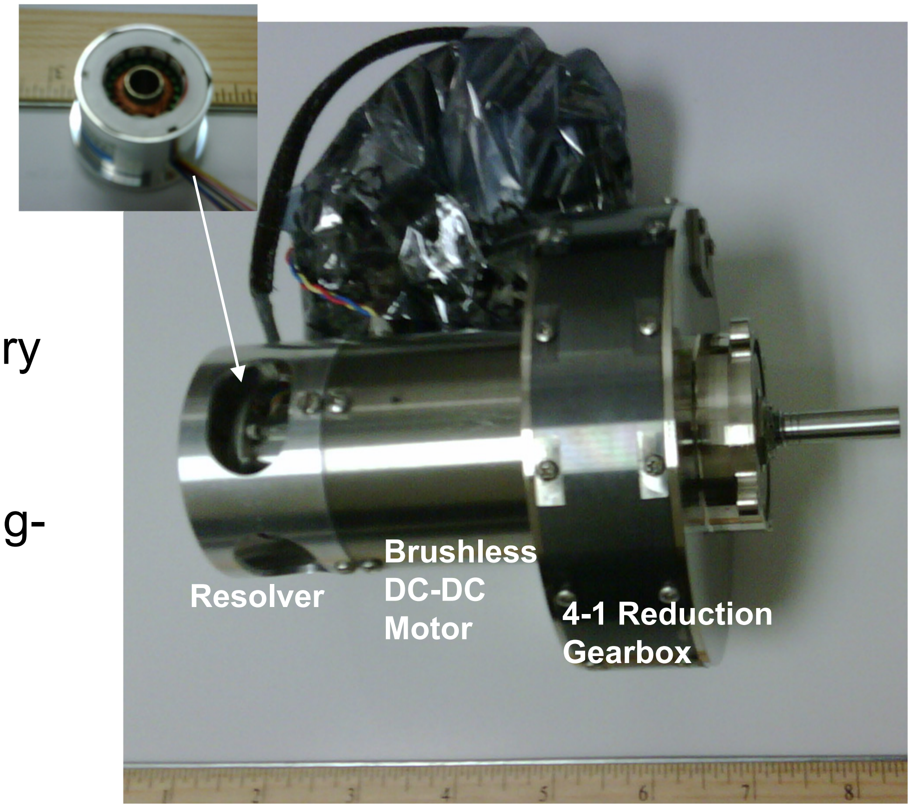
LTM0 mounted in the LTM low temperature test bed



Chamber Performance

LTM0, WSA motor (100W) with dry lubed bearings and single stage 4:1 reduction planetary gear box

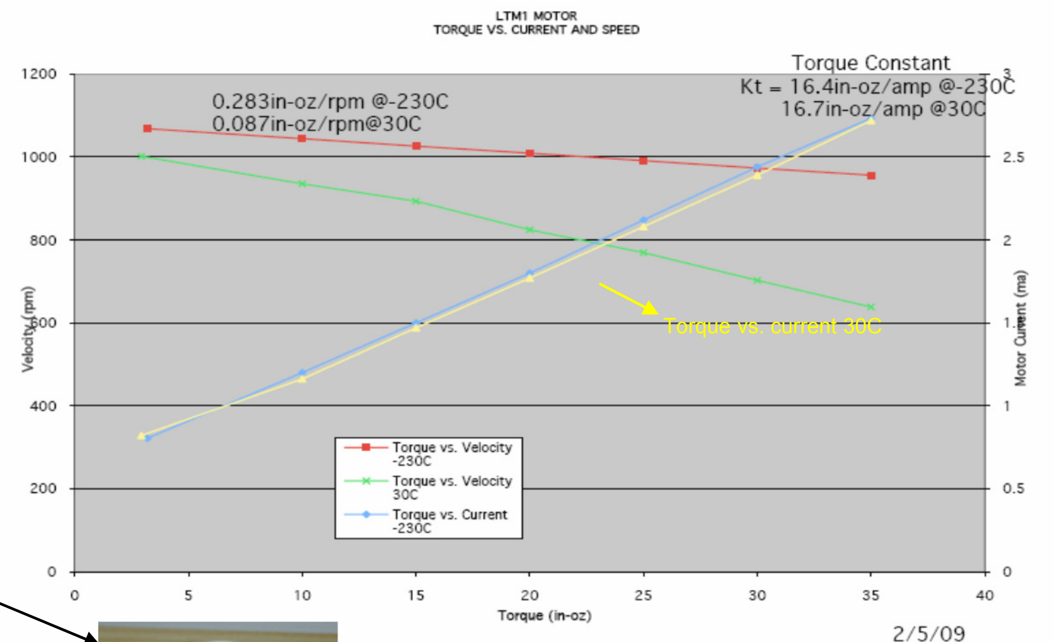
- LTM0 which consist of the modified MSL Wheel Steering Actuator with dry lubricated bearings together with a custom long life dry lubricated 4-1 speed reduction gearbox and bearing-less resolver.
- Initially LTM0 was tested at room temperature and also at -170C and operated satisfactorily within the specification.

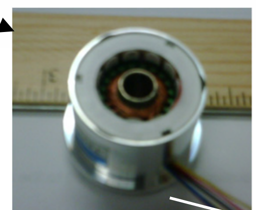


LTM0, first version of the Low Temperature Mechanism designed to function between -230C and 120C

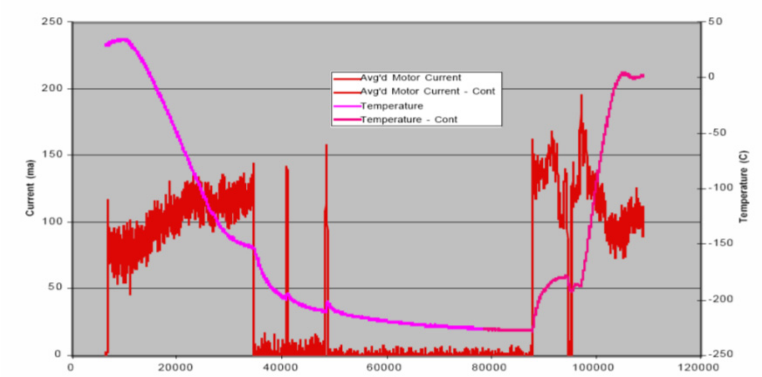
Characterization of LTM0 30C and -230C

- LTM1 was tested at LaRC vacuum temperature test chamber
- The use of the dry lubricant produced torque constant that is almost independent of temperature.

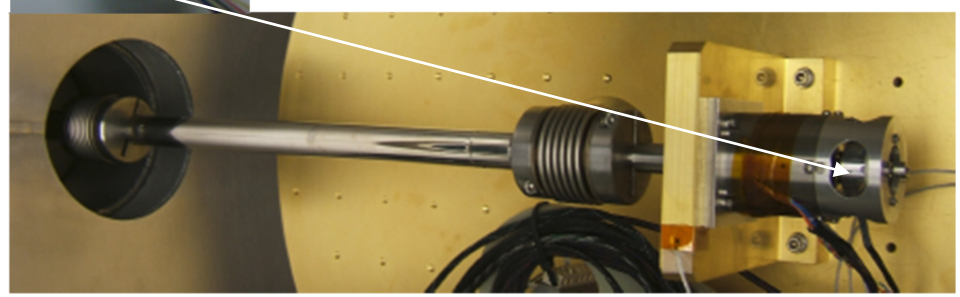




Torque, speed performance LTM1 at room temperature and -230C



No Load Motor test to -230C at LaRC



LTM1 in LaRC temperature test-bed

LTM0 extended life test to KPP goal reached 90 million revolution

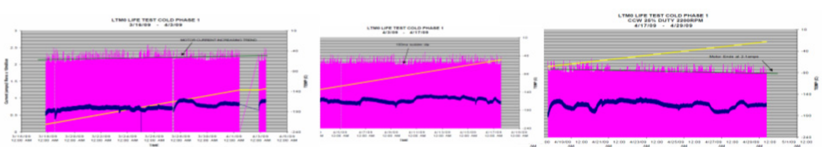
Deploy the LTM0 into LaRC chamber, complete 100M rev low temperature life test and pre/post life test characterization

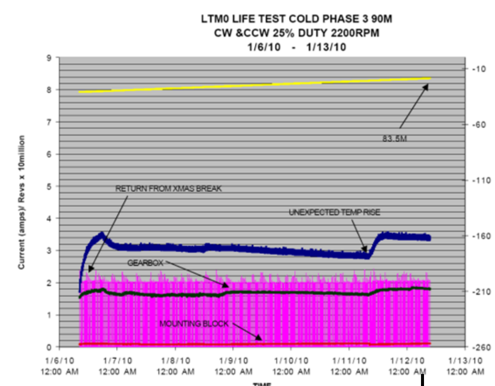
- Chamber temperature set at 20 K
- JPL motor controller was used to drive LTM
- Motor current and casing temperature were used as monitor
- LTM0 met and exceeded the KPP threshold.
- Motor current remained steady for the 90 M revolution

LTM under test at LaRC test bed

Aeroflex actuator, LTM0 (Motor, Single stage gear box & resolver)

90 million revolution low temperature life test results for LTM0 at LaRC test bed

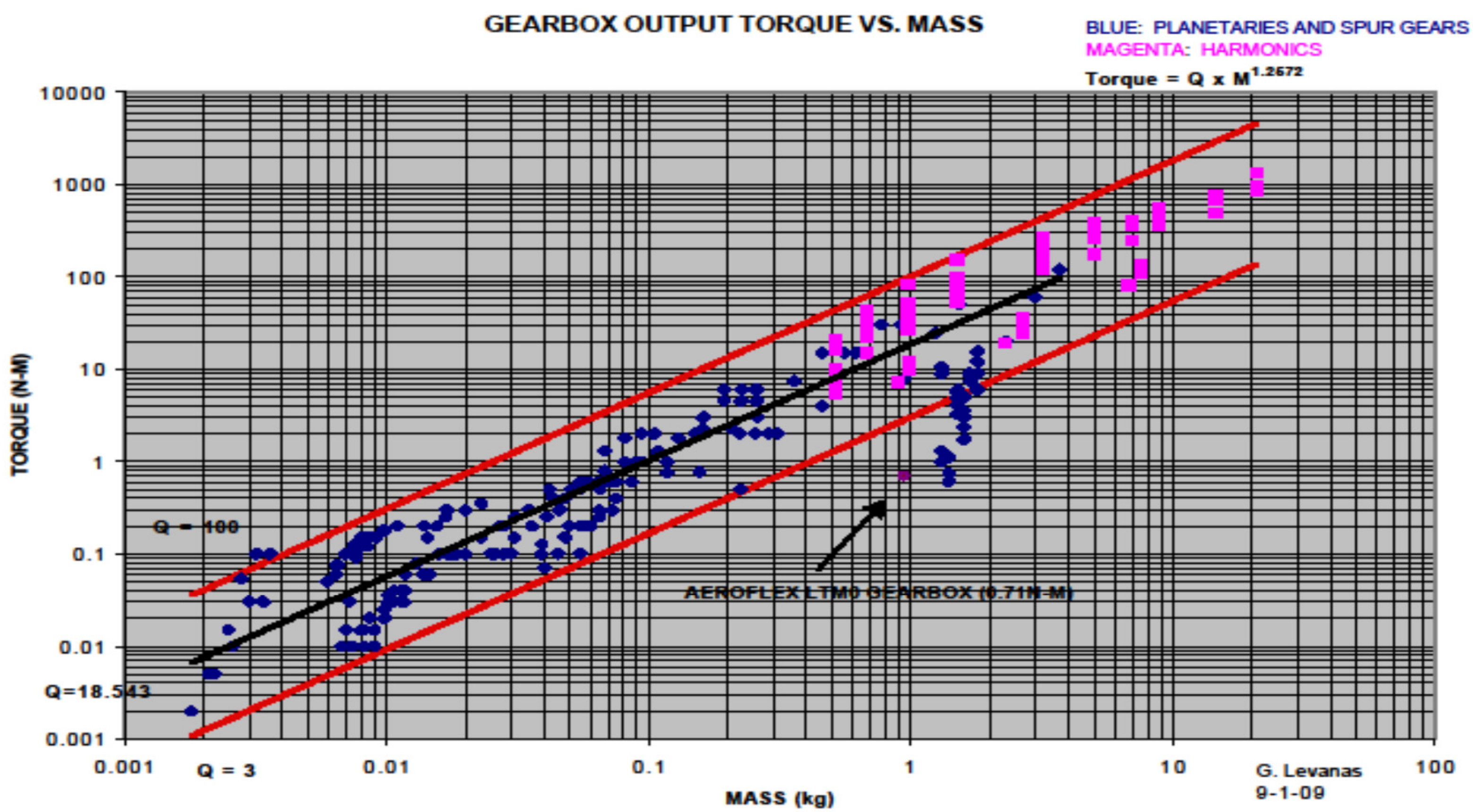




10M 20M 30M …………….. 90M

# of rev in Millions

Accomplishment : LTM0 performance benchmark



Next Step: LTM1 consisting of motor, resolver, multi stage gear box and dust seal

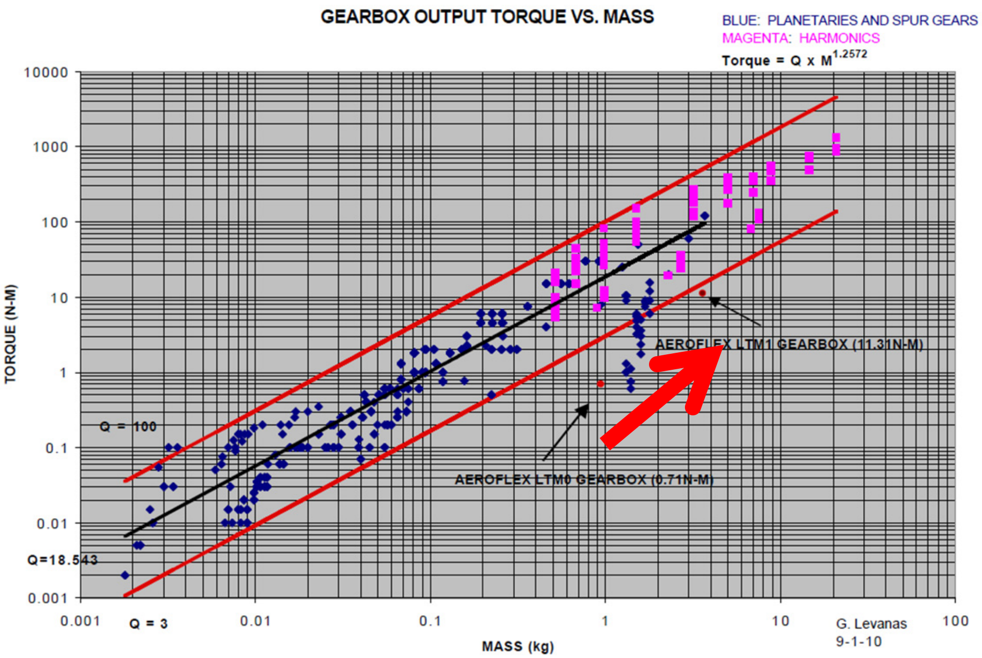
LTM1, a 100W mechanism with multi-stage gear box, resolver and dust seal, capable of operating minimum 30M Rev at -230C

- Successfully completed fabrication of LTM1

Significance:

- First article of its kind, high torque long life low temperature actuator with competitive specific torque density

Assembled LTM1



Torque-Mass benchmark LTM1

Technology Gaps – Low Temp Mechanism

- **Light weight medium power LTM**
  - Significant mass payback for robotic applications
  - Requires development of light weight Gears

- **Large power long life low temperature mechanism (TRL-1)**
  - Needed for human explorations
  - Significant payback in decreased system complexity and increased modularity and robustness

- **Long Life, Low Temperature Resolver (Current TRL - 3)**
  - Position sensor of choice for actuators
  - Predominant failure mode corrected but not validated

- **Low temperature actuator control electronics (Current TRL 3-4)**
  - Critical low temperature sub circuits demonstrated using SiGe BiCMOS tech
  - Potential for miniaturization and performance enhancement
  - Potential for cable length and noise reduction